ESTIMATING THE AGE OF PAPER INSULATION IN 33/11 KV DISTRIBUTION POWER TRANSFORMERS USING MATHEMATICAL MODELLING

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ABSTRACT

The oil-paper insulation in power transformers is subjected to various stresses due to environmental conditions, voltage and fault stresses. Such stresses can cause deterioration of the oil-paper insulation in transformers. The condition of oil can be reversed back with the help of present technology such as on-line oil filtration. The degradation of paper insulation, however, is irreversible. Thus, the life of a transformer can be effectively determined by the life of its paper insulation. When paper degrades, it produces several by-products such as CO, CO_2, and Furans and they migrate to the oil. There has been a growing trend throughout the world to study and estimate the deterioration of insulation strength of paper using such by-products as indicators. There are more direct approaches to obtain indications of paper insulation degradation such as Tensile Strength (TS) and Degree of Polymerization (DP) measurements of paper. But these approaches require shutdown on the transformer and are considered intrusive. Therefore, this paper attempts to estimate the age of paper insulation in 33/11 kV Power Transformers by using a Mathematical Modelling based on the by-products of paper insulation degradation.

INTRODUCTION

The most commonly used insulating materials in transformers are paper and mineral oil. Basically, apart from providing overall insulation to the transformer, the mineral oil acts as coolant to the transformers, assisting in extinguishing arcs, and dissolves gases and moisture produced arising out of various phenomena within the transformer [1]. Whereas paper, it provides insulation to the conductor in the transformer windings.

Presence of $\mathbf{H_2O}$ (water or moisture) in paper insulation has been linked to the decomposition of the paper fibers that is irreversible and eventually causes the paper to lose its mechanical and dielectric strength [2,3]. As for $\mathbf{O_2}$ (oxygen), its presence causes oxidation on the mineral oil that leads to the deterioration on the oil insulation quality and the formation of acids. With acids present in the mineral oil, paper insulation is again exposed to deterioration and eventually ageing [3].

Ageing of paper insulation has been directly linked to its mechanical strength [2,4]. Studies have been done focusing on how long the paper can retain its mechanical strength as it ages before it loses its dielectric strength. Studies have also been done to estimate the life of transformers by studying the life of the paper insulation [4,5].

PAPER INSULATION DEGRADATION

The paper used as insulation in transformers is mainly cellulose fibers that consist of cellulose molecules that lay side by side to other cellulose molecules. Each cellulose molecules have different length and these different groups of cellulose molecules are held adjacent to each other via the hydroxyl group (-OH). Each cellulose molecule consists of a linear glucose molecule polymer. These glucose molecules or the D-anhydro-glucopyranose units are held together through a β-1, 4-glycosidic bond as indicated in Figure 1a and 1b [6] below:

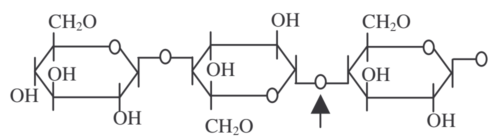

Figure 1a: Structural Formula of Cellulose

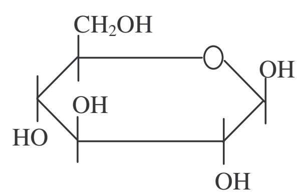

Figure 1b: Structural Formula of Glucose

The number of glucose molecules forming on the cellulose chain determines the length of the cellulose molecules. The differing length of the cellulose molecules has been used as the base for measuring the strength of the cellulose molecules that is also known as the Degree of Polymerization (**DP**). Basically, **DP** denotes the average number of glucose units per cellulose molecules. The higher the number of glucose units per cellulose molecules, the higher the **DP** is [3]. Generally, new paper insulation has a DP of 1200 and paper insulation is deemed to reach its useful life limit when the DP is measured at 200 [7].

Three most common degradation factors of cellulose have been identified as thermal, oxidative, and hydrolytic [3].

Thermal Degradation

When the cellulose is exposed exclusively to heat up to

200ºC, the beta linkages or glycosidic bonds tend to break and open the glucose molecule rings. By-products of this reaction include **free glucose molecules, moisture (H_2O), CO, CO_2, and organic acids** [3].

Oxidative Degradation

The presence of oxygen **(O_2)** promotes oxidation which cellulose molecules are prone to. The reaction of oxidation on these cellulose molecules causes the glycosidic bond to weaken and can cause scission to the cellulose molecule chain. Moisture **(H_2O)** is the by-product from this oxidative reaction [3].

Hydrolytic Degradation

With water and acids present, the glycosidic bond is exposed to slicing which in turn produces free glucose [3].

Degradation By-Products

It can be observed that the immediate by-products related to paper degradation are **CO**, **CO_2**, moisture **(H_2O)**, organic acids and free glucose molecules. Presence of **H_2O** and organic acids in the mineral insulating oil can further degrade the free glucose molecule into 5-hydroxymethyl-2-furfuryl or **5H2F** [3].

5H2F is an unstable compound and can decompose further into 4 other furaldehyde or Furans that includes furfuryl alcohol (**2FOL**), 2-furaldehyde (**2FAL**), 2-acetyl furan (**2ACF**), and 5-methyl-2-furfuryl (**5M2F**) [3].

H_2O and organic acids, even though are produced through paper insulation degradation, are also present due to other reasons such as moisture leakage into the transformer, mineral oil degradation, and absorption of **O_2** from the atmosphere.

USING THE BY-PRODUCTS AS INDICATORS TO PAPER INSULATION CONDITION

From the previous discussion, **CO**, **CO_2**, and Furans can be regarded as appropriate indicators to paper insulation condition. Furans are deemed appropriate as indicators to paper insulation condition due to the fact that Furans are exclusive by-products of paper degradation. [3,7].

CO and CO_2

The formation of **CO** and **CO_2** can be due to the degradation of cellulose or paper insulation and such formation increase rapidly with higher temperature. A ratio of **CO_2/CO** in Rogers Ratio Method of analysis is useful in determining whether a fault is affecting the paper insulation. It should be noted that Rogers Ratio Method of analysis aids in analyzing fault i.e. gives an indication what problems exist in the transformer rather than detecting fault. Since **CO** and **CO_2** can also be produced from mineral insulating oil degradation, additional indicators, such as Furans, are still needed to support the analysis using **CO_2/CO** ratios. [1]

Furans

Furans concentration has been shown to have direct links to **DP** and **TS** of the paper insulation. Researchers have concluded that Furans concentration increases over time as more cellulose degrades over time. **DP** and **TS**, on the other hand, decrease over time [5]. These two findings concluded that ageing in paper insulation causes an increase in Furans concentration found in the mineral insulation oil but at the same time indicated that ageing reduces the **DP** and **TS** of paper.

Studies have shown that of all the 5 Furans above, **2FAL** can be found in abundance if compared to the other compounds [2]. It has also been proven that **2FAL** is the most stable of all Furans [8]. From these two findings, **2FAL** can be considered as the choice indicator to paper insulation degradation.

MATHEMATICAL MODELLING

Data from 16 selected transformers were used to develop a mathematical model to help estimate the **DP** of paper insulation based on **CO**, **CO_2**, **CO_2/CO**, and **2FAL** as:

DP = f (CO, CO_2, CO_2/CO, 2FAL)……………...………(1)

Non-Linear Relationship between Age and Degradation By-Products Concentration

The following non-linear relationships were observed between the paper degradation by-products (**CO**, **CO_2**, **2FAL**) and the transformers age.

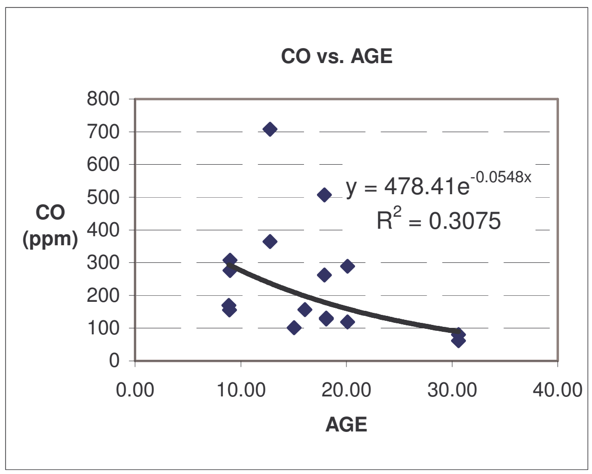

Figure 2: Relationship between CO and Age

From Figure 2, the relationship between CO and Age can be written as:

$$CO = Ae^{-B.Age} \quad \text{……(2)}$$

and after applying log natural (ln) to both sides of the equation, Equation (2) can be simplified as:

$$Y_1 = a_0X_1 + a_1 \quad \text{……(3)}$$

where Y_1 = Age and X_1 = lnCO.

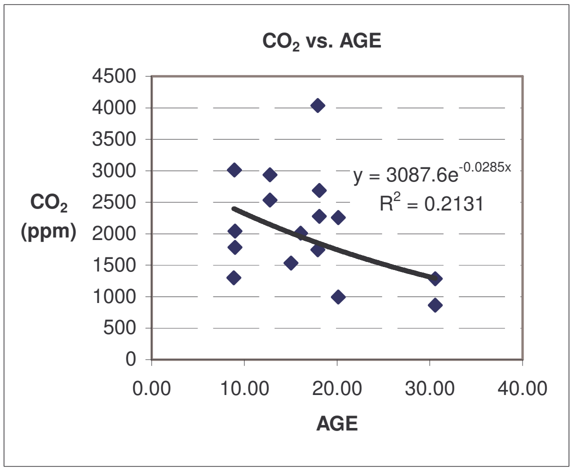

Figure 3: Relationship between CO_2 and Age

Similarly, Figure 3 illustrates that the relationship between CO_2 and Age that can be written as:

$CO_2 = Ae^{-B.Age}$ ……………………………….(4)

and simplified as:

$Y_2 = a_2X_2 + a_3$ …………………..……………(5)

where Y_2 = Age and $X_2 = \ln CO_2$.

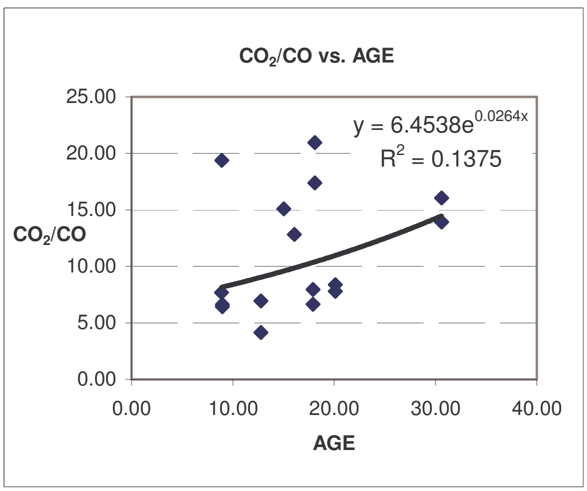

Figure 4: Relationship between CO_2/CO and Age

Figure 4 indicates the relationship between CO_2/CO and Age and can be written as:

$CO_2/CO = Ae^{-B.Age}$ ……………………………(6)

and eventually, simplified as:

$Y_3 = a_4X_3 + a_5$ …………………………………(7)

where Y_3 = Age and $X_3 = \ln(CO_2/CO)$.

By using a similar approach, Figure 5 shows the relationship between 2FAL and Age and can be written as:

$2FAL = Ae^{-B.Age}$ ………………………………(8)

and simplified as:

$Y_4 = a_6X_4 + a_7$ ………………………………..(9)

where Y_4 = Age and X_4 = ln2FAL.

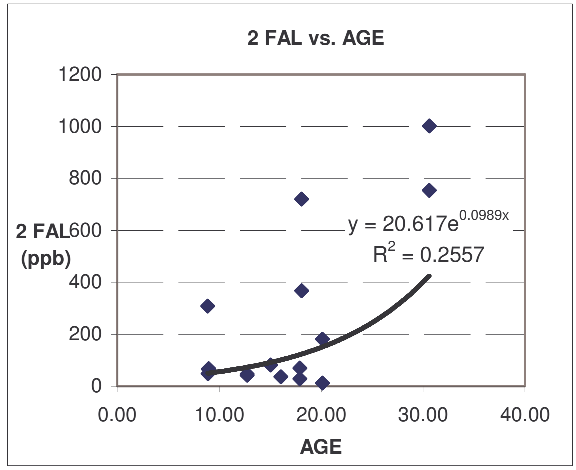

Figure 5: Relationship between 2FAL and Age

From the above relationships between the degradation by-products (**CO**, **CO_2**, **2FAL**) and the transformer age, and the fact that the paper insulation DP reduces over time, Equation (1) can be written as :

$DP = f\ (Y_1, Y_2, Y_3, Y_4)$ …………………..…(10)

Weightages of the Degradation By-Products

During the paper degradation processes, the generation of the **CO**, **CO_2**, and **2FAL** can vary depending upon numerous factors such as the temperature, faults, and chemical properties of paper. Thus, the weightages of the degradation by-products are regarded to be different i.e. k_1, k_2, k_3, and k_4 are weightages that are assigned to **CO**, **CO_2**, **CO_2/CO**, and **2FAL** respectively.

The mathematical modeling must also satisfy the boundary condition as given below:

$k_1 + k_2 + k_3 + k_4 = 1$ ……………………….....(11)

where k_1, k_2, k_3, and k_4 should be between 0.1 and 0.7.

Thus, to relate DP with **CO**, **CO_2**, **CO_2/CO**, and **2FAL**, the proposed mathematical model shall include the respective weightages as follows:

$DP = k_1Y_1 + k_2Y_2 + k_3Y_3 + k_4Y_4$ ……………(12)

where Y_1, Y_2, Y_3, and Y_4 is the relationship between **AGE** and the concentration of **CO**, **CO_2**, **CO_2/CO**, and **2FAL** respectively. By applying Equations (3), (5), (7), and (9), Equation (12) can be written as:

$$\boldsymbol{DP = k_1\ (a_0X_1+a_1) + k_2\ (a_2X_2+a_3) + k_3\ (a_4X_3+a_5) + k_4\ (a_6X_4+a_7)} \quad \text{……..(13)}$$

Actual DP Measurement

With the paper extraction done on 5 transformers, actual DP measurements are as in Table 1:

No.	TX ID	Year of Service	DP Value
1	3	21	825
2	4	21	945
3	7	18	940
4	8	18	985
5	9	13	921

Table 1: Actual DP Measurement

From the above measurement, there is a general trend between transformer age and **DP** i.e. in normal operational condition, the higher the age of a transformer, the lower the **DP** value is. However, other factors such as exposure to high fault current can influence the **DP** measurement as shown by TX No. 9.

Development of the Mathematical Model

By using multiple linear regression technique and software codes, the constants of the proposed ***DP Estimation Mathematical Model*** are determined and Table 2 shows the values of the weightages and constants:

Weightages		Constants	
k_1	0.40	a_0	98.89
k_2	0.10	a_2	0.02
k_3	0.10	a_4	-668.42
k_4	0.40	a_6	-72.21

Table 2: Values for Weightages and Constants

and

$$k_1*a_1 + k_2*a_3 + k_3*a_5 + k_4*a_7 = \underline{1127.68}$$

Thus, the ***DP Estimation Mathematical Model*** is:

$$\mathbf{DP = (39.56)*\ln CO + (0.002)*\ln CO_2 + (-66.842)*\ln(CO_2/CO) + (-28.88)*\ln(2FAL) + (1127.68)}$$

The values of the constants are obtained with high precision with the calculated RMS error being 0.003851212.

Validation of the Mathematical Model

Based on the above ***DP Estimation Mathematical Model***, the calculated DP value is compared with the actual DP for TX No. 8. The calculated DP is 1098.58 as compared to the actual measurement of 985. The percentage error is reflected in the MAE calculated as 8.72%.

CONCLUSION

This proposed multiple linear regression technique has demonstrated its efficiency in developing a complex non-linear real world function in order to estimate the DP of the paper insulation. However, higher accuracy can be achieved if unknown factors that can influence the results of this mathematical model can be controlled and better samples are used during the study.

From the mathematical model, it can be observed that **2FAL** and **CO** has the higher weightages when compared to **CO_2** and **CO_2/CO**. Such results can be expected since **2FAL** is an exclusive by-product of paper degradation while **CO** is the major gas produced when cellulose is exposed to high temperature thermal heating.

The above ***DP Estimation Mathematical Model*** can be used to estimate the DP of the paper insulation and eventually the age of transformers with a confidence level of 91.28% and should be further developed to improve on its accuracy.

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